

Estimating Coastal Turbidity using MODIS 250 m Band Observations

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ABSTRACT

Terra MODIS 250 m observations are being applied to a Suspended Sediment Concentration (SSC) algorithm that is under development for coastal case 2 waters where reflectance is dominated by sediment entrained in major fluvial outflows. An atmospheric correction based on MODIS observations in the 500 m resolution 1.6 and 2.1 micron bands is used to isolate the remote sensing reflectance in the MODIS 250m resolution 650 and 865 nanometer bands. SSC estimates from remote sensing reflectance are based on accepted inherent optical properties of sediment types known to be prevalent in the U.S. Gulf of Mexico coastal zone. We present our findings for the Atchafalaya Bay region of the Louisiana Coast, in the form of processed imagery over the annual cycle. We also apply our algorithm to selected sites worldwide with a goal of extending the utility of our approach to the global direct broadcast community.

INTRODUCTION

Monitoring suspended sediment distribution in the coastal zone is challenging. Accessibility and comprehensive sampling are two significant challenges making it impractical to monitor coastal zones using surface based efforts. Use of aircraft such as the NASA ER-2 is helpful for research activities but impractical for continuous monitoring. Satellite based observations provide the best possible source of data for operational monitoring. The advent of MODIS [1] on the Terra (launched in Dec. 1999) and Aqua (launched in May 2002) platforms has provided well calibrated 250 m resolution radiances useful as a test-bed for sediment concentration estimates and daily global monitoring. These bands (Table 1) are well positioned for monitoring high sediment concentration in case 2 waters.

Previous work using Multi-spectral Atmospheric Mapping Sensor (MAMS) remote sensing observations from the ER-2 platform showed that spectral bands located in the red and near infrared portion of the spectrum are useful for discriminating the reflectance of various suspended sediment concentrations (SSC) found in case 2 waters along Louisiana's Gulf coast [2]. The in-water portion of the at-sensor signal received in these bands originates in the few meters of the water column, largely eliminating sub-aqueous bottom reflectance as a source. A SSC algorithm was generated using the MODIS Airborne Simulator (MAS) [3] observations at 660 nm [4]. This paper investigates the

use of similar bands on MODIS for estimating SSC along the Louisiana Gulf Coast. The algorithm developed depends upon the sediment inherent optical properties (IOPs) of a specific sediment type. In-water radiative transfer modeling was performed with Hydrolight [5], a code for computing radiance distributions and derived quantities for natural water bodies. Atmospheric correction is achieved with the assistance of look-up tables generated by 6S [6], an atmospheric radiative transfer code designed to simulate the radiance reflected by the earth-atmosphere system as observed by a range of satellite sensors.

Primary purpose	Band [spatial resolution]	Bandwidth (nm)	Signal to noise ratio	Clear water penetration depth	SSC algorithm
Land/Cloud/Aerosols Boundaries	1 [250 m]	620 - 670	128	2.4 m	Low sediment concentration
	2 [250 m]	841 - 876	201	22 cm	High sediment concentrations
Land/Cloud/Aerosols Properties	3 [500 m]	459 - 479	243		
	4 [500 m]	545 - 565	228		
	5 [500 m]	1230 - 1250	74		
	6 [500 m]	1628 - 1652	275	1.6 mm	Atmospheric correction
	7 [500 m]	2105 - 2155	110	0.41 mm	Atmospheric correction

Table 1. Characteristics of MODIS 250 m and 500 m bands [1]. The clear water penetration depths are computed from the complex refractive index data of Kou et al. [11].

BACKGROUND

The Atchafalaya Bay (Fig. 1) receives the effluent of the Atchafalaya River, a distributary of the Mississippi River. The Atchafalaya River carries about 33% of the total discharge from the Mississippi River distributary system to the Gulf of Mexico. The effluent provides the building material to form delta lobes in the Atchafalaya Bay, as well as supplying a persistent, yet varying quantity of material (suspended load concentrations up to 1000 mg/l or more) for transport in the coastal zone. The coarse grained material settles to the sub-aqueous bottom; fine-grained material is generally transported to sites down-drift of the Atchafalaya Bay. The sediment represents a resource valuable to combat the ongoing natural subsidence of the Louisiana coast region. Subsidence causes loss of wetland habitats by allowing salt water to invade coastal freshwater environments. Sediment transport (or lack of it) is responsible for hazards to industries, including siltation of navigation channels, destructive saltwater intrusion into freshwater environments, and destruction of forests, wetlands and nursery grounds important to commercial fisheries. Coastal fisheries management techniques in Louisiana's fresh and brackish marsh environments depend in part on sediment transport dynamics. For example, in Louisiana where about 31% of the total U.S. commercial shrimp harvest is

landed [7], nursery habitat is threatened by increasing erosion of tidal marshes and reduced access to nursery habitat through construction of water control structures [8]. Marsh surfaces must vertically accrete by gaining new marsh soil if they are to counter submergence and salt water intrusion [9]. Also, shifting patterns of fresh, salt and brackish waters affect productivity and survival of oyster beds.

In the micro-tidal Louisiana coastal zone, sediment plume distribution is strongly affected by local winds, especially associated with frequent cold front passages [4]. These winds vary on the scale of hours to days, modulating the direction and speed of the near-shore currents that transport the suspended sediment. Monitoring sediment loads and transport reveals information on the distribution of the resource in the coastal zone and on the natural processes that drive the distribution.

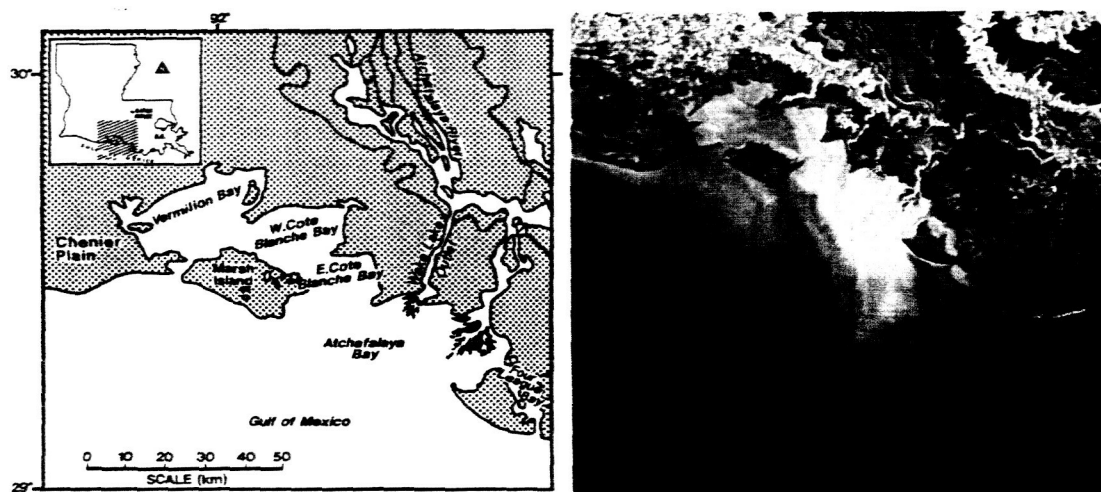


Figure 1. Atchafalaya Bay Region of Louisiana Coastal Zone. True color Terra MODIS image shown at right depicting sediment plume distribution on March 21, 2001.

ATMOSPHERIC CORRECTION

The ultimate goal of this work is to provide to the direct broadcast community an algorithm for estimating coastal suspended sediment concentrations that can be adjusted for local sediment IOPs. Central to this task is the retrieval of the water column reflectance in MODIS channels sensitive to the presence of suspended sediment. In the coastal zone spatial resolution is important and we choose to work with the two 250 m MODIS bands centered at approximately 650 nm and 850 nm (Table 1). A common approach to over-ocean atmospheric correction is to characterize the atmospheric contribution to observed reflectance in a spectral region where the ocean water column has zero reflectance. MODIS has 500 meter resolution bands at 1.6 μm and 2.1 μm where we may safely assume that the water column reflectance is zero except, perhaps, where marine biota have congregated on the water surface as in the case of coccolithophore blooms and red tides.

For radiative transfer we employ the same formalism as Taftaa [10], that is,

$$\rho_{obs}^* = T_g \left(\rho_{atm}^* + \rho_{sfc}^* + \frac{\rho_w t_u t_d}{1 - s \rho_w} \right), \quad (1)$$

where ρ_{obs}^* is the apparent reflectance observed by the satellite sensor, T_g is the gaseous transmittance along the sun-surface-satellite path, ρ_{atm}^* is the atmospheric path reflectance, ρ_{sfc}^* is the ocean surface apparent reflectance, t_u and t_d are the upwards and downwards scattering transmittances, respectively, s is the atmospheric spherical albedo and ρ_w is the reflectance of the ocean water column. Equation (1) can be inverted to provide ρ_w only if certain other quantities can be estimated from model computations. We have used the 6S radiative transfer model to compute values for T_g , ρ_{atm}^* , ρ_{sfc}^* , t_u , t_d and s for three aerosol models (continental, maritime and urban) and five optical depths. Presently these computations are performed for spatial domains within each MODIS overpass, each domain defined as 2 scan lines along-track by 2 degrees of scan angle cross-track. Ozone and water vapor column amounts, required for the calculation of the gaseous transmittance, are taken from global TOVS and GDAS1 gridded forecast fields for the time closest to the satellite overpass. The wind speed and direction are also taken from the GDAS1 file, estimates of these being needed to compute ρ_{sfc}^* .

For MODIS bands 6 and 7, ρ_{obs}^* is computed on the assumption that ρ_w is zero. For each pixel, the squared distances between observed and model apparent reflectances are computed. That is, for each aerosol atmosphere k ,

$$d_k = \left(\frac{\rho_{obs}^k(6) - \rho_{obs}^*(6)}{T_g(6)} \right)^2 + \left(\frac{\rho_{obs}^k(7) - \rho_{obs}^*(7)}{T_g(7)} \right)^2, \quad (2)$$

where ρ_{obs}^k indicates the model predicted apparent reflectance for aerosol model k (in contrast to the satellite measured reflectance ρ_{obs}^*). Each of the unknown quantities in equation (1) (ρ_{atm}^* , ρ_{sfc}^* , t_u , t_d and s for MODIS bands 1 and 2) are computed as X in,

$$X = \frac{\sum_{k=1}^m X_k / d_k}{\sum_{k=1}^m 1 / d_k}, \quad (3)$$

where the summation is over the m aerosol atmospheres defined for model simulations. Inverting equation (1) and substituting these estimates of ρ_{atm}^* , ρ_{sfc}^* , t_u , t_d and s provides, for each 250 m pixel, the water column reflectance ρ_w in MODIS bands 1 and 2. Fig. 2 shows ρ_w of Louisiana coastal waters on March 21, 2001.

A difficulty that remains is the removal of sun glint in regions where it is a significant contributor to the total reflectance. The current atmospheric correction relies entirely on modeled values of ρ_{sfc}^* which is adequate only for regions of low sun glint. A data driven correction based on combined visible, 4 μm and 11 μm observations will be investigated in the future.

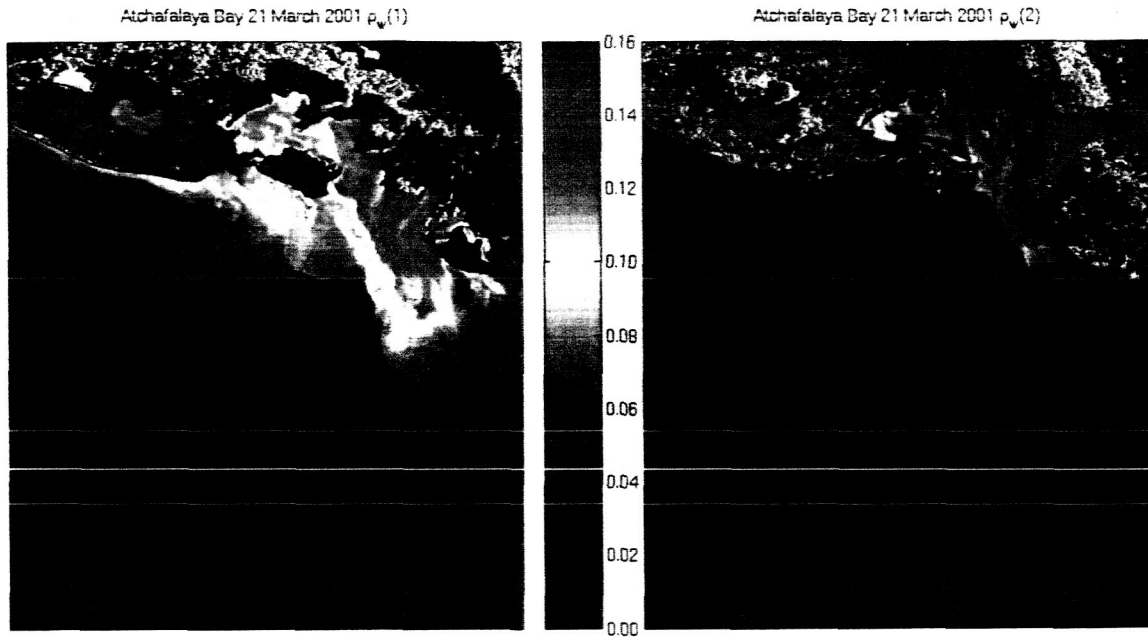


Figure 2. Retrieved ρ_w for coastal waters in the Atchafalaya Bay region of the Louisiana coast on March 21, 2001. Band 1 water column reflectance (left) is greater than for band 2 (right) primarily due to a larger backscatter coefficient and a greater penetration depth.

SEDIMENT CONCENTRATION RETRIEVALS

The absorption and scattering coefficients of the suspended sediment are computed from specific absorption and scattering coefficients, a^* and b^* respectively, of dimension area per unit mass. Multiplication by sediment concentration yields absorption and scattering coefficients (a_s and b_s) of dimension inverse length, that is,

$$a_s = S a^* \quad \text{and} \quad b_s = S b^* \quad , \quad (4)$$

where S is the sediment concentration in milligrams per liter. Using aircraft based observations from previous work [12] we have found that the Atchafalaya Bay sediment is similar to the Hydrolight sediment model denoted "brown earth". Sediments scatter anisotropically and, in this work, we assume that the ratio of sediment backscatter to total scatter is 0.02. The total absorption coefficient, a , and the total backscattering coefficient, b_b , are given by,

$$a = a_w + a_s \quad \text{and} \quad b_b = 0.5 b_w + 0.02 b_s \quad , \quad (5)$$

where a_w and b_w are the absorption and scattering coefficients for water. We wish to estimate the remote sensing reflectance for both MODIS bands 1 and 2 in order to retrieve a suspended sediment load. Hydrolight simulations, however, are limited to the wavelength range 350 to 800 nanometers. Fig. 3 shows the remote sensing reflectance, R_{rs} , versus b_b/a for "brown earth" simulated by Hydrolight for MAS bands 3, 4 and 5

(662, 709 and 751 nm respectively). A line of best fit, with slope 0.052 and zero intercept, is also shown. Based on these simulations we choose to estimate R_{rs} via,

$$R_{rs} = 0.052 \frac{b_b}{a} \quad (6)$$

and we further assume that $\rho_w = \pi R_{rs}$. Equations (4) to (6) permit an estimate of S from ρ_w for each of MODIS bands 1 and 2 provided that water and sediment inherent optical properties are known. Inverting equation (6) leads to,

$$S = \frac{50\pi a_w \rho_w - 0.052 \times 25\pi b_w}{0.052 b^* - 50\pi a^* \rho_w} \quad (7)$$

We used values from Kou et al. [11] for a_w and for b_w we used the empirical relation $b_w = 2.935 (\lambda/100)^{-4.3}$. Values for a^* and b^* were taken from the "brown earth" model in Hydrolight for MODIS band 1, and were extrapolated to provide estimates for MODIS band 2. The ratio of MODIS band 2 ρ_w to MODIS band 1 ρ_w is also a function of suspended sediment concentration,

$$\left(\frac{\rho_w(2)}{\rho_w(1)} \right) = \left(\frac{0.5 b_w(2) + 0.02 b^*(2) S}{a_w(2) + a^*(2) S} \right) \left(\frac{a_w(1) + a^*(1) S}{0.5 b_w(1) + 0.02 b^*(1) S} \right) \quad (8)$$

and is not affected by the angular distribution of the ocean water column radiant exitance which is similar in MODIS bands 1 and 2. Fig. 4 shows $\rho_w(1)$ and $\rho_w(2)/\rho_w(1)$ as a function of S for the Hydrolight "brown earth" sediment model. It is clear that $\rho_w(1)$ provides good sensitivity at low sediment concentrations whereas $\rho_w(2)/\rho_w(1)$ has good sensitivity at higher concentrations.

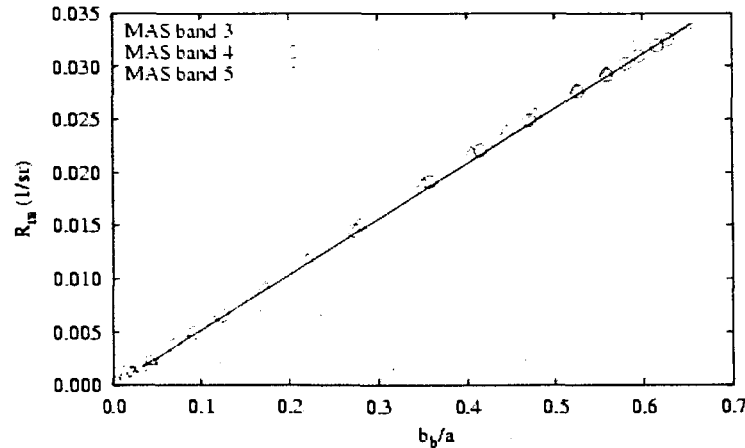


Figure 3. Remote sensing reflectance, R_{rs} , versus b_b/a for "brown earth" simulated by Hydrolight for MODIS Airborne Simulator (MAS) bands 3, 4 and 5 (662, 709 and 751 nm respectively). The line of best fit has slope 0.052 and passes through the origin. Hydrolight simulation results are for nadir view with the sun at 40 degrees from zenith.

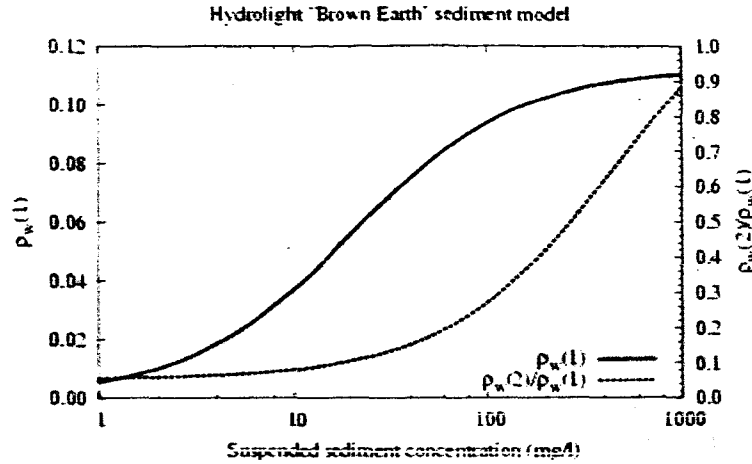


Figure 4. MODIS $\rho_w(1)$ as a function of suspended sediment concentration (left axis) and $\rho_w(2)/\rho_w(1)$ as a function of suspended sediment concentration (right axis) for the Hydrolight “brown earth” sediment inherent optical properties.

For present purposes we set $\rho_w(1)$ thresholds at 0.04 and 0.08. Pixels with $\rho_w(1) < 0.04$ use the MODIS band 1 sediment concentration retrieval, pixels with $\rho_w(1) > 0.08$ use the MODIS band 2/1 ratio retrieval. For $0.04 < \rho_w(1) < 0.08$ a linear combination is returned as the sediment concentration.

Fig. 5 shows Atchafalaya Bay sediment concentrations retrieved in this way from four MODIS overpasses chosen to represent each of the four seasons of the year 2001. Because of its greater water penetration depth, the results of a MODIS band 1 only suspended sediment retrieval are also shown in Fig. 5. The SSC retrieval for these 4 days is indicative of the annual cycle of turbidity along the Louisiana coast. Springtime snowmelt and rain increase discharge from the Mississippi River distributary system and sediment loads in the Atchafalaya Bay region (March 21 case). As spring runoff subsides, the Atchafalaya Bay sediment diminishes into the summer (May 24 case) and fall (Sept. 29 case) seasons. At the onset of winter, cold front passages return, increasing wave activity and sediment re-suspension in the coastal zone (Dec. 30 case). Cold fronts swell and subside the suspended sediment load during frontal passages and the quiet interim periods, respectively.

The MODIS band 1 only retrieval in Fig. 5 is “saturated” (red region) in the high SSC regions for the March 21 and Dec. 30 cases. This occurs because the MODIS band 1 calculated value for $\rho_w(1)$ exceeds the maximum value of $\rho_w(1)$ based on the “brown earth” model in Figure 4. This suggests that the IOPs for brown earth are not matching the IOPs of the Atchafalaya Bay suspended sediment. Raising the backscatter to total scatter ratio from the assumed 0.02 up to 0.03 or 0.04 would raise the brown earth model $\rho_w(1)$ to include the MODIS band 1 calculated value for $\rho_w(1)$ in the saturated regions. However, no firm evidence is available at this time to substantiate adjusting the IOPs in the model for the Atchafalaya Bay suspended sediment retrieval. In the future, the use of in situ measurements of SSC in the Atchafalaya Bay will be investigated for deriving IOPs for the region.

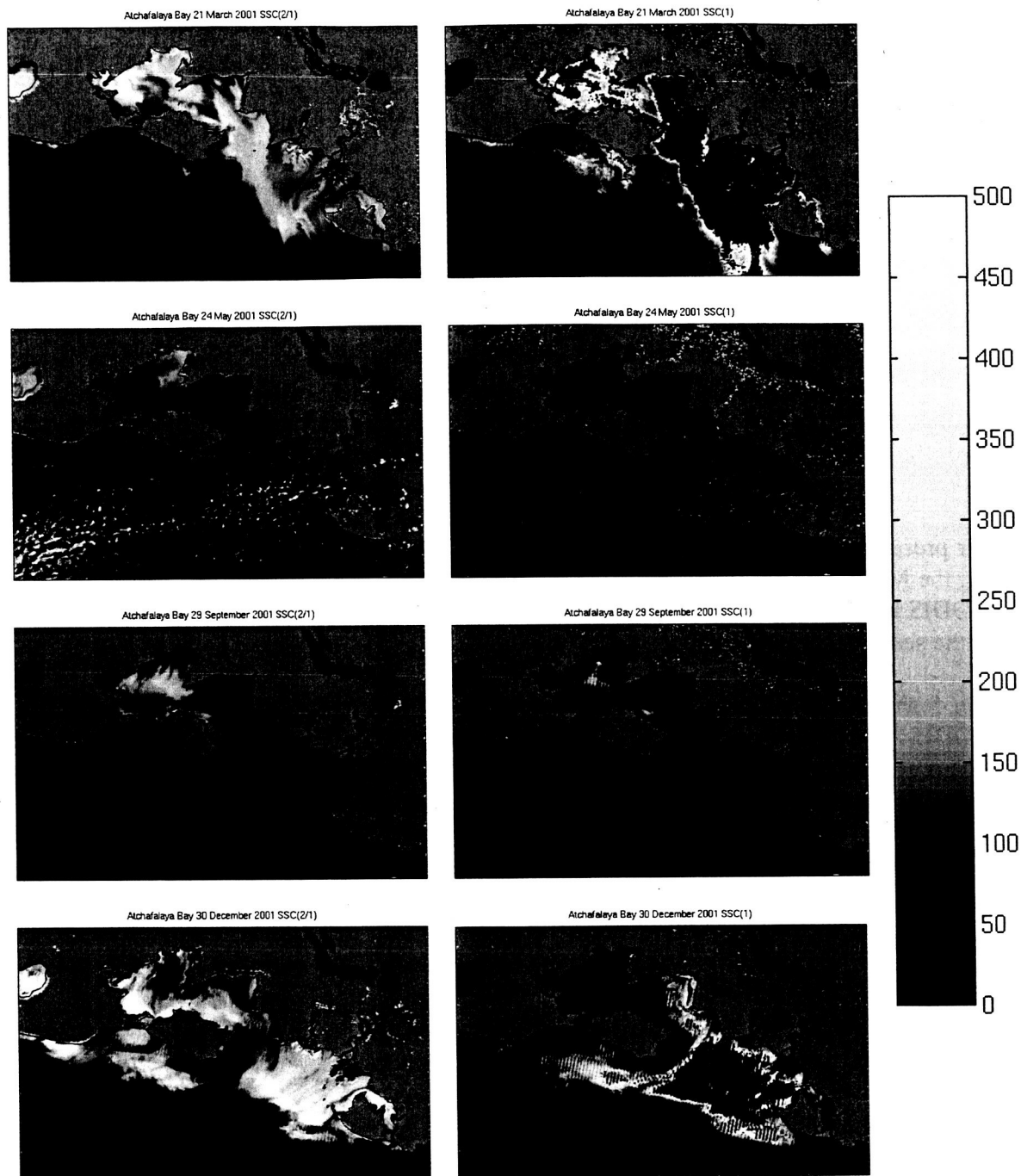


Figure 5. Suspended sediment concentration in mg/l retrieved for the Atchafalaya Bay region from four MODIS overpasses chosen to represent each of the four seasons. The leftmost images are derived using the combined band 1 and band 2 approach, the rightmost images use only band 1. In the 21 March and 30 December at right, the algorithm fails when $\rho_w(1)$ values exceed the maximum predicted by the in-water model (red regions). This indicates that the assumed IOPs for band 1 may be underestimated for the Atchafalaya Bay region.

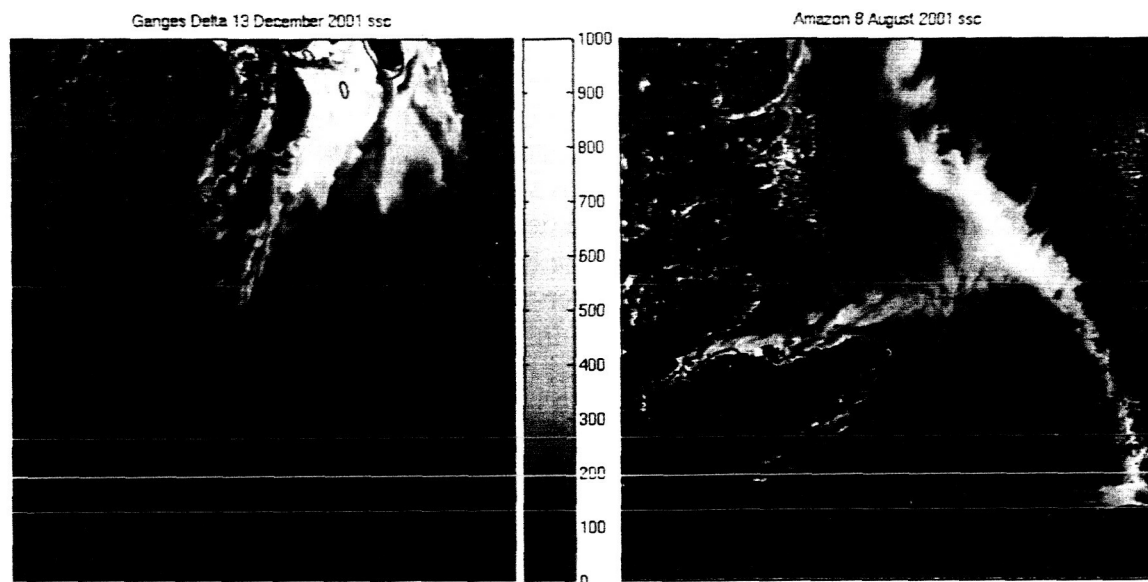


Figure 6. Suspended sediment concentration in mg/l retrieved for the Ganges Delta on December 13, 2001 (left) and for the Amazon Delta on August 8, 2001 (right).

Fig. 6 gives a first look at the application of the MODIS SSC algorithm to other prominent world deltas. The products, which use the same IOPs as used for the Atchafalaya Bay region, are interesting for the relative variability in the scenes but are not intended to be used for SSC quantity comparisons between delta regions. These examples are presented as initial test cases for extending the application of the SSC algorithm to the global domain, the goal of this effort. The SSC retrieval at sites around the globe is a function of the IOPs at each site. The IOPs at each site must be substantiated by in situ sampling before the SSC quantity at different sites can be meaningfully compared. It is envisioned that local users of a MODIS SSC direct broadcast product will apply their knowledge of local drainage basin conditions to specify appropriate IOPs. The first step of making the MODIS SSC retrieval product available to local users for their evaluation is being undertaken by this project.

CONCLUSIONS AND FURTHER WORK

A suspended sediment concentration estimation algorithm has been tested using MODIS observations of case 2 waters along the Louisiana coast. MODIS provides well calibrated on-orbit observations of the globe on a daily basis, including 660 and 865 nm bands at 250 m resolution. The MODIS 250 m resolution observations are used to estimate SSC. MODIS 500 m observations at 1.64 and 2.13 μm are used to constrain the atmospheric correction of the 660 and 865 nm data. Atmospheric modeling of aerosol is based upon the 6S model. Inherent optical properties for relating the remote sensing reflectance to SSC are provided in the Hydrolight model. Early testing indicates that low (< 50 mg/l) SSC is best retrieved using the MODIS 660 nm band; however, the sensitivity of the 660 nm band to SSC diminishes at high concentrations and so a ratio technique of the 865 and 660 nm bands is used. SSC "snapshots" of the case 2 waters in the Atchafalaya Bay

region show a large range of SSC both on given days and through the annual cycle. The algorithm was also applied without adjustment to scenes of the Ganges and Amazon River deltas for a first look at the SSC variability at these sites.

Further work is necessary to mature the SSC algorithm. A key element is to better understand the IOPs of the sediment at given delta sites around the world. Observations in the Atchafalaya Bay region suggest that the backscatter to total scatter ratio of 0.02 is an underestimate. Co-incident aircraft observations and in situ measurements in the Louisiana coast region will be used to gain insight on this ratio for that region. Such measurements are needed and sought for other deltas around the world, with a goal of a daily MODIS global product of SSC for case 2 waters.

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